Mine Burial Induced by Local Scour and Sandwaves

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LONG-TERM GOALS

Our long term goal is to help advance the U.S. Navy's capabilities for Mine Burial Prediction (MBP) by conducting large-scale laboratory observations that will both improve our knowledge of the physical processes involved in mine burial and provide a vital bridge between field experiments and numerical modeling of mine burial processes in shallow waters.

OBJECTIVES

The main objective of this effort has been the direct observation and monitoring of the burial process of finite-length cylinders (model mines) induced by the combined action of waves, currents and pure oscillatory flows. The experimental conditions have made it possible to observe the burial process due to both local scour around the mines as well as the passage of large sandwaves. These rather unique observations will be used to test, validate, and calibrate numerical model predictions and will also help in the development of a mechanistic model for Mine-Fluid-Sediment (MFS) interaction by the ONR Mine Burial Prediction Team.

APPROACH

Our approach has been mainly an experimental one. We have conducted laboratory experiments with two special-purpose facilities. One facility is the Large Oscillating Water Sediment Tunnel (LOWST) constructed with DURIP support. LOWST can reproduce field-like conditions near the sea bed. The second facility is a multipurpose wave-current flume which is 4 feet (1.20 m) deep, 6 feet (1.8 m) wide, and 161 feet (49.2 m) long. It has a 30 cm deep movable sediment bed where model mines can be placed and scour tests conducted under the action of waves and currents. Experiments have been conducted with both a single mine as well as multiple mines. This approach has been particularly useful to assess the role of sandwaves in the burial process.

Our research team consists of the PI and four Graduate Research Assistants, Yovanni Catano (PhD 2005), Xiaofeng Liu (PhD candidate), Salih Demir (MS 2005) and Blake Landry (PhD student).

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WORK COMPLETED

Wave Tank: More than two hundred experiments were carried out in the wave-current flume. The main task completed within this effort has been the characterization of the burial process induced by both local scour as well as the passage of sandwaves with superimposed ripples. It is found that the burial of a finite-length cylinder is determined by local scour around the cylinder and by a more global process associated with the formation and evolution of sandwaves having superimposed ripples on them. Depending on the ratio of the amplitude of these features and the body's diameter (D), a model mine can progressively get partially or totally buried as such bedforms migrate. Table 1 shows a list of the cylindrical models that were tested. Experiments were conducted with Reynolds wave number and Keulegan-Carpenter number within the ranges of $104 \leq Rew \leq 1.7\text{x}105$ and $2 \leq KC \leq 71$, respectively. Analysis of the experimental data indicates that existing semi-empirical formulae for prediction of equilibrium-burial-depth, geometry of the scour hole around the cylinder, and time-scales developed for pipelines are not suitable for the case of a cylinder of finite length.

Table 1. Properties of test cylinders

Cylinder Material	Conc. 1	Conc. 2	Conc. 3	Conc. 4	Conc. 5	Alum. 1	Alum. 2	Steel 1	Steel 2
Diameter (cm)	25.4	20.3	15.2	12.5	10.2	8.6	8.6	5.1	7.6
Length (cm)	102	81.3	30.5	25.4	20.3	26.2	35.1	20.3	20.3
Aspect ratio, *ar*	0.25	0.25	0.50	0.50	0.50	0.32	0.25	0.26	0.37
Specific gravity, γc	2.0	2.0	2.3	2.3	2.3	2.7	2.7	7.85	7.85
R. height, *ks* (mm)	0.8	0.8	0.8	0.3	0.8	0.1	0.1	0.3	0.3

Oscillatory-flow tunnel: about 30 experiments have been completed with the Large Oscillating Water-Sediment Tunnel (LOWST). Mainly, burial due to scour under pure oscillatory motion was studied. Observations were made with two camcorders, one in each side of the model cylinder during the scour and burial process. Three different model cylinders (mines) were tested in the range of $4 < KC < 70$. Interestingly, the length to diameter ratio, the density as well as the initial burial of the models were found to be ineffective on the final burial depth. The scour process for cylindrical objects was clearly identified. Currently used Carstens-Martin and HR Wallingford burial equations were tested and found to be inadequate for burial estimations in our experiments. A new equation for estimating the final burial depth was proposed.

RESULTS

Wave Tank Results: Scour pattern around a cylinder is shown in Figure 1a. Relative burial depth (Bd / D) is found to be mainly a function of two parameters. One is the Keulegan-Carpenter number, KC, (Fig. 1b), and the other one is the Shields parameter, θ (Fig. 2). Data scatter was found to be less for the Shields parameter, although a similar trend is present for both, waves alone and combined flows. A similar behavior was observed when plotting relative burial depth as a function of the cylinder Reynolds wave number, Rew, (Fig. 3). In both cases the trend for combined flows is below the one for waves alone. Combining θ, KC and the ratio of wave velocity to wave plus current velocity, it is observed that all measured data can be represented by the following expression

$$\frac{B_d}{D} = \frac{6}{25}\left(\frac{U_m}{U_m + U}\right)(\theta \ KC)^{2/5} \tag{1}$$

One can conclude that such expression does a fairly good job for prediction purposes, as shown in Fig. 4. For the measured data, the previous equation was found to be more accurate than the predictor formulas derived for pipelines by Sumer et al. (2001) and for short cylinders by Voropayev et al. (2003).

Burial-time scales seem to be influenced by both *KC* and the Shields parameter, θ, as shown in Fig. 5. Length and width of the scour hole around a given cylinder at equilibrium conditions, for WA and CF, were found to be primarily a function of the Keulegan-Carpenter number, *KC*, and the cylinder aspect ratio, *ar*, through the following empirical relationship:

$$\frac{L_{st}}{D} = \frac{3}{4} a_r^{3/10} KC^{3/5} \tag{2}$$

This formula is physically congruent with the governing hydrodynamic conditions and represents a better agreement with the present measured data than other existing formulae (Fig. 6).

At equilibrium conditions, it was observed that the width of the scour hole, Ws / D, tended to a constant value of 4 regardless the type of flow, i.e. under waves alone or combined flow.

The present experimental evidence suggests that higher burial depths correspond to the case when the angle of attack is 900 (Fig. 7). For smaller initial angles of attack, perturbation of the flow due to the own presence of the body is not as pronounced leading to smaller burial depth. Lower burial depths are obtained when the initial rotation is 00.

Scour hole width is also shown to be orientation dependant. This quantity increases with increasing α. The final angle of orientation is primarily a function of the Shields parameter, θ. The final orientation, αf, depends also on the specific density of the cylinder. That is, under similar hydraulic conditions, the final orientation is larger for lighter cylinders than for denser cylinders regardless cylinder characteristics. Cylinders with initial orientations of 00 and 900 did not turn regardless cylinder properties.

Development and evolution of sandwaves has been identified as a major agent on the global mine burial process. Ripples superimposed on sandwaves vary in size and shape depending on their relative position along the sand wave. The study of both types of features is of vital importance for the proper understanding of the flow-bed interaction and the resulting bed morphodynamics. Bedforms shape and evolution influence the flow pattern over the bed and the flow interacting with the cylindrical object. The present experimental work has also been extended to the study of formation and evolution of both, ripples and sandwaves. Experimental data had been collected describing length, height, steepness and migration speed. For instance, Fig. 8 shows measured migration speeds for sandwaves while Fig. 9a shows sandwave length as a function of the Reynolds wave number and the surface water wavelength. In particular sand wave size and migration speeds seem to play a major role in the mine burial process due to progressive covering and uncovering of the cylinder. Once they start development, it can be observed that they travel in the direction of the wave propagation. Sandwaves have a very well defined sinusoidal pattern when pure wave motion is imposed, however for the case of waves plus currents

they start to emulate the shape of dunes as in the case of unidirectional flow (Fig. 9b). Existing predictive formulae for sandwave length and migration speed deduced from analytical analysis, in particular those dealing with linear and weakly nonlinear analysis; seem not to be in good agreement with the present experimental data.

When sandwaves interact with a cylinder, the scour hole may be reduced until it disappears (Fig. 10). During the un-burial process of the cylinder, the scour pattern may return to a similar configuration of that governed by local scour.

Oscillatory Tunnel Results: Experimental observations showed that the main mechanism of burial by scour is as follows: scour starts from the shoulders of the cylinder and tends to move towards the center. As the net downward force on the cylinder exceeds the bearing capacity of the remaining soil beneath the cylinder, sinking occurs. Since it is nearly impossible to have a perfectly symmetric scour shape, one end of the cylinder falls into the scour pit first and this causes small tilting of the model cylinder. After a while, the other end of the cylinder falls. This process, sinking of one end followed by the other (with decreasing increments, but in a much slower way) repeats itself many times. After this point, two different burial mechanisms were observed as follows:

1) The process might continue as described above until final burial depth. (Fig. 11a) In the final burial state, the maximum scour depth is located at the ends of the cylinder and some sand is accumulated in the middle at a height of around half the cylinder diameter.

2) Sinking of one end of the cylinder might not be compensated with the sinking of the other end. In this case, the model stays tilted, without regaining a horizontal position. (Fig. 11b) Generally, this type of behavior was seen at high flow conditions.

Under *local scour*, it was found that the main parameter affecting the final burial depth of a finite length cylinder lying on a sandy sea bottom under wave action is the Shields parameter. For experiments conducted in the LOWST, the dependence of the equilibrium burial depth on the Shields parameter was very strong (Fig. 12) and better described by the expression,

$$\frac{Bd}{D} = 2\theta^{0.8} \tag{3}$$

With a correlation coefficient of $\rho^2 = 0.96$. However, the burial time-scale seems to depend on both the Shields parameter and the Keulegan-Carpenter number.

To simulate the necessary conditions to obtain *fluidization* of the bed, few experiments were conducted in the LOWST. The primary purpose of these experiments was to properly define the value of the Shields parameter from where liquefaction starts to be the main mechanism for burial of cylindrical objects. A range for the Shields parameter from 0.7 to 0.8 was identified in the present experiments, as the transitional zone of burial mechanisms, from local scour to bed fluidization. This result is not surprising, since Shields parameter values near this range have been observed to cause the wash out of existing bedforms sand the return to flat bed conditions.

Two different responses of cylindrical objects to such high flow conditions were observed in the experiments. Fast burial and rolling motion cases were observed as illustrated in Figs. 13 and 14, respectively. The Shields parameter values for both conditions were very similar with $\theta \approx 1$. Fig. 13

shows that, as the sediment underneath the cylinder moves as a layer, the cylinder sinks very rapidly, mainly because of its high density, ρc = 7.8 gr/cm3. Typical final burial depths observed in “fast burial” experiments were around half diameter below the mean bed surface (i.e. $Bd / D \approx 1.5$). However, when cylinders made up of lighter material were used, i.e. ρc = 2.7 gr/cm3, the cylinders rolled back and forth, with the same phase of the flow velocity. The amplitude of the horizontal displacement of the cylinders with respect to its original position was the same in both directions.

IMPACT/APPLICATIONS

Our observations indicate that the mine burial mechanism is a complex process. Mine burial under either waves or combined flow, is influenced by two different processes. One is related to the *local scour* around the mine, which takes place within the first few hundred minutes of flow action (i.e. short time scale). Another process that can influence the final burial depth has been identified and is related to the development of sandwaves which in turn may partially or totally cover a given mine as they migrate (i.e. long time scales). This process could be dubbed as *global burial*. Existing formulations for mine burial do not account for the dynamics of long sandwaves, thus suggesting that a probabilistic approach would have to be followed in order to predict the vertical displacement and burial of a given mine. Our findings suggest the need to produce two kinds of models for mine burial prediction. The first kind should be able to reproduce local scour around an object (i.e. mine) for small space and time scales. The second kind should be capable of predicting the dynamics of long sandwaves, including their interaction with bottom objects, over much larger space and time scales. ONR’s Mine Burial Prediction Program has ongoing efforts along these modeling approaches. The observations reported herein can be used to test and improve such models.

RELATED PROJECTS\

Within the Mine Burial Prediction Program there are a number of related projects that will be using our observations to test numerical predictions of mine burial. Our group is currently conducting experiments with non-cylindrical model mines. New equipment for measuring in LOWST is being procured with a DURIP grant N00014-06-1-0661.

AWARDS

Professor Marcelo Garcia received the 2006 Hans Albert Einstein Award from the American Society of Civil Engineering (ASCE).

that need to accounted for before using the empirical equations obtained in the laboratory for field predictions.sive models re

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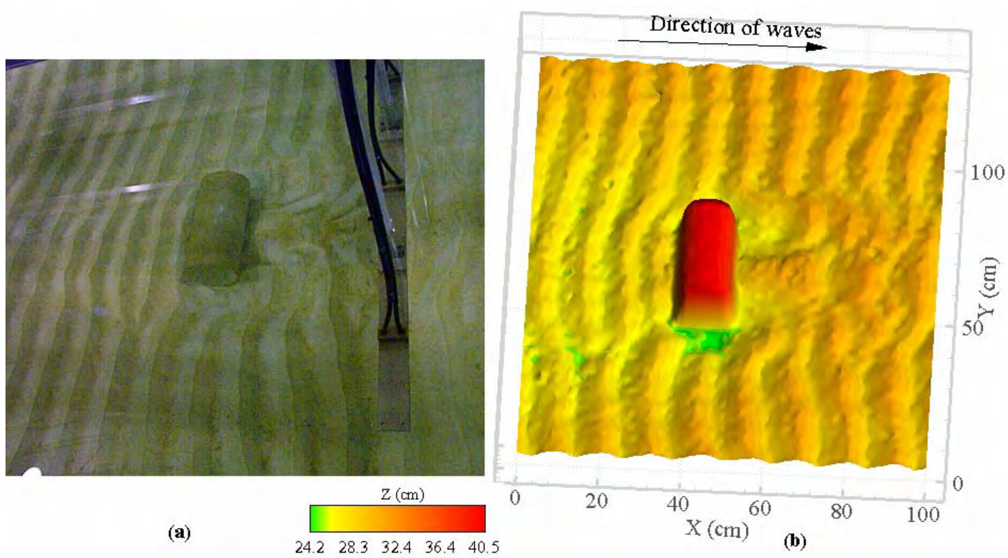


Fig. 1a: Local scour pattern around cylinder for the case of waves alone after 95 minutes run in the wave tank. Hydraulic conditions: Hw = 17.4 cm, Tw = 2.3 s, Lw = 4.6 m, h = 56 cm. Cylinder # 2 in Table 1.

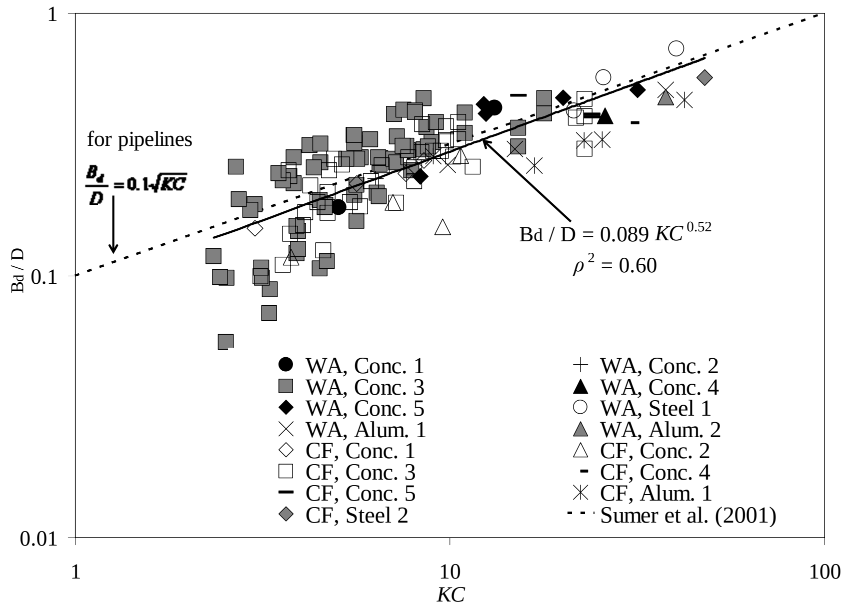


Fig. 1b. Equilibrium relative burial depth as function of the KC number for a cylinder placed on a sand bed. Waves alone and combined flow, live bed ($\theta > \theta cr$)

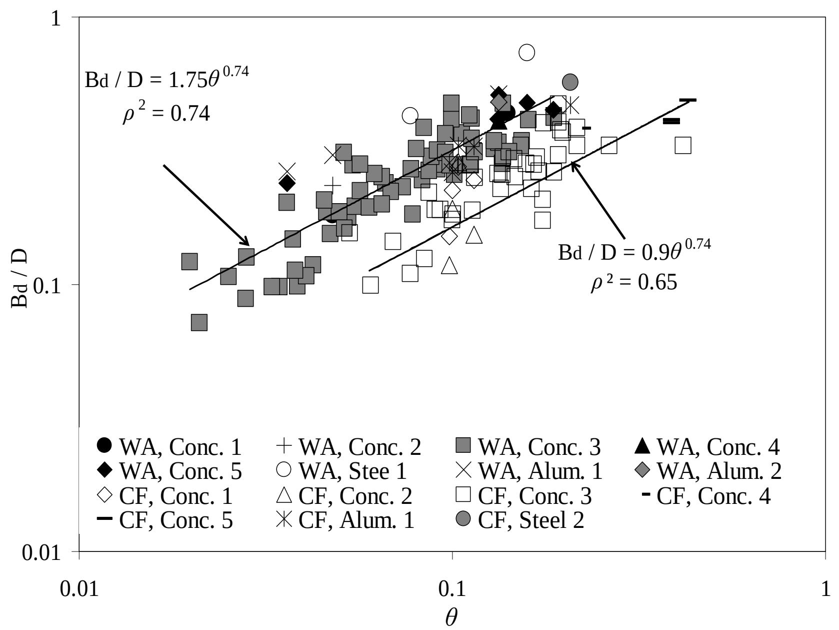


Fig. 2. Equilibrium burial depth as a function of the Shields Parameter θ. Experiments conducted in the wave flume.

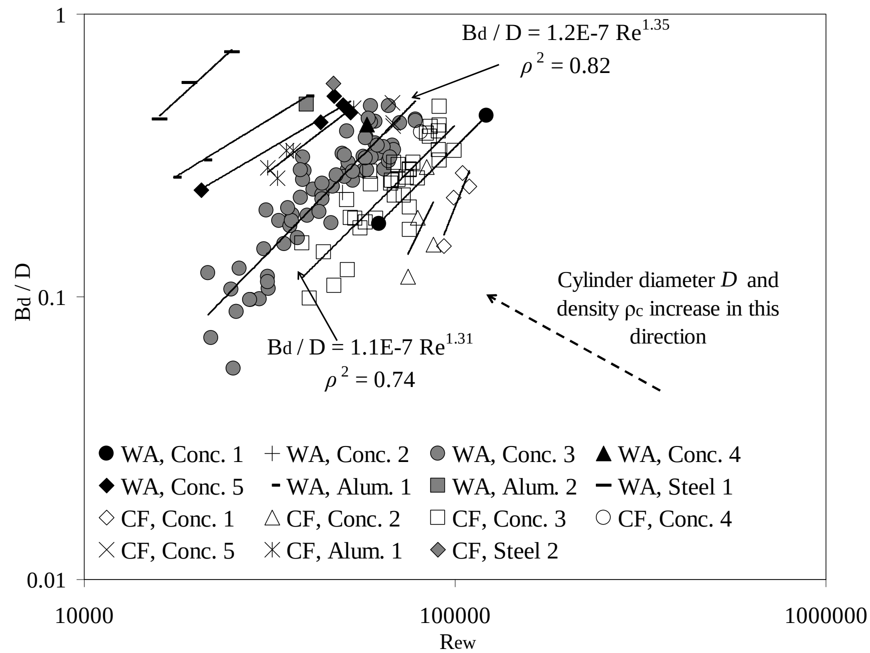


Fig. 3. Equilibrium burial depth as function of the cylinder Reynolds wave number. Both cases: waves alone and combined flow, live bed ($\theta > \theta cr$).

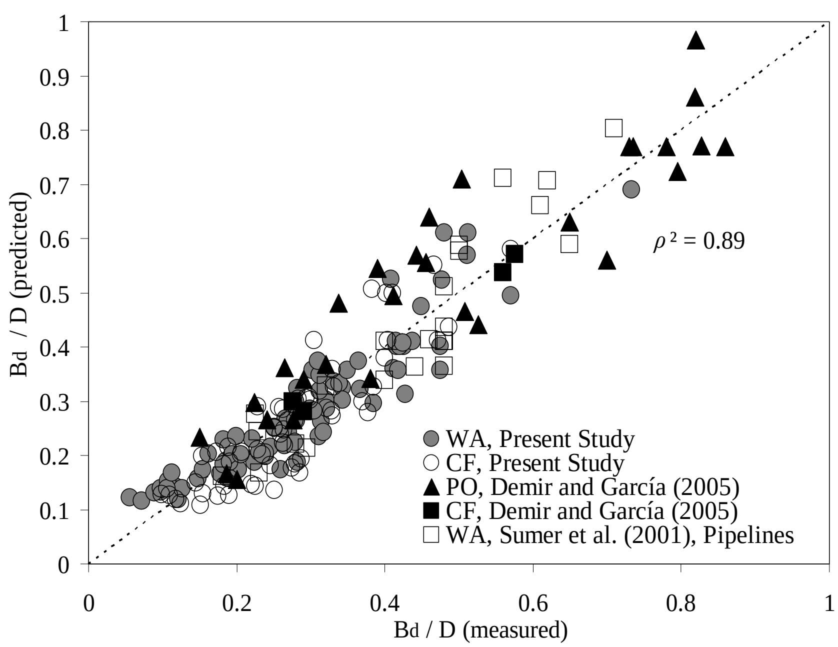


Fig. 4. Measured final relative burial depth from the present study and from other researchers. Predicted values are obtained by using Eq. 1.

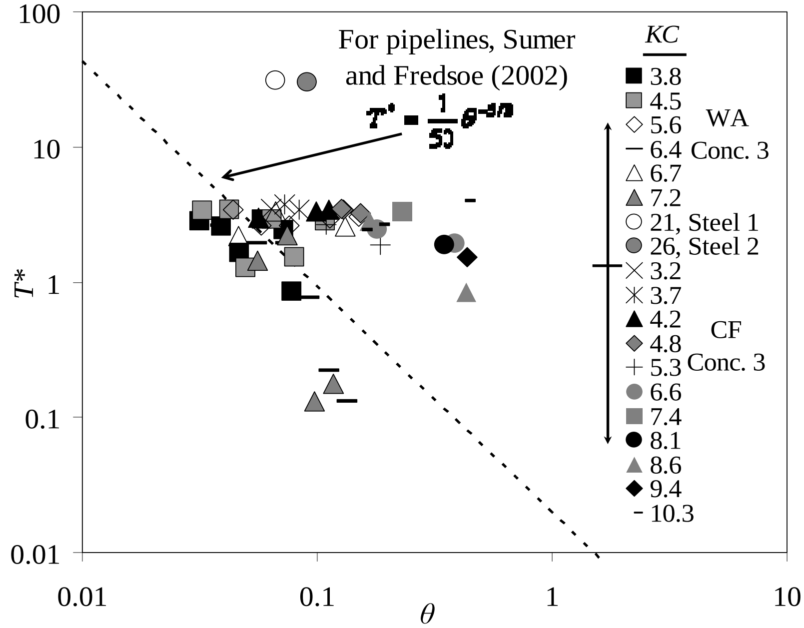


Fig. 5. Dimensionless time scale T* as function of the Shields parameter, θ, and the Keulegan-Carpenter number, KC. Waves alone and Combined flow, Live bed, (θ > θcr). Comparison with the case of self-burial of pipelines at span shoulders in a steady current, Sumer and Fredsoe (2002).

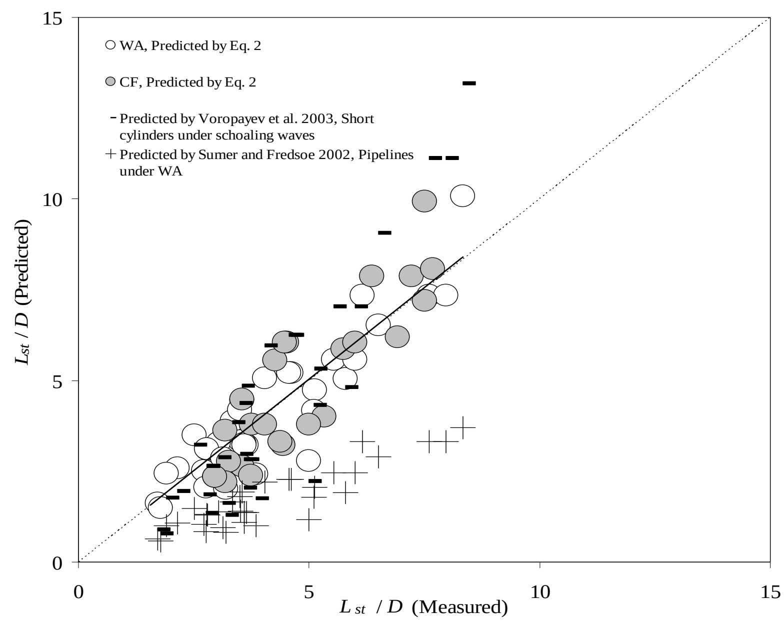
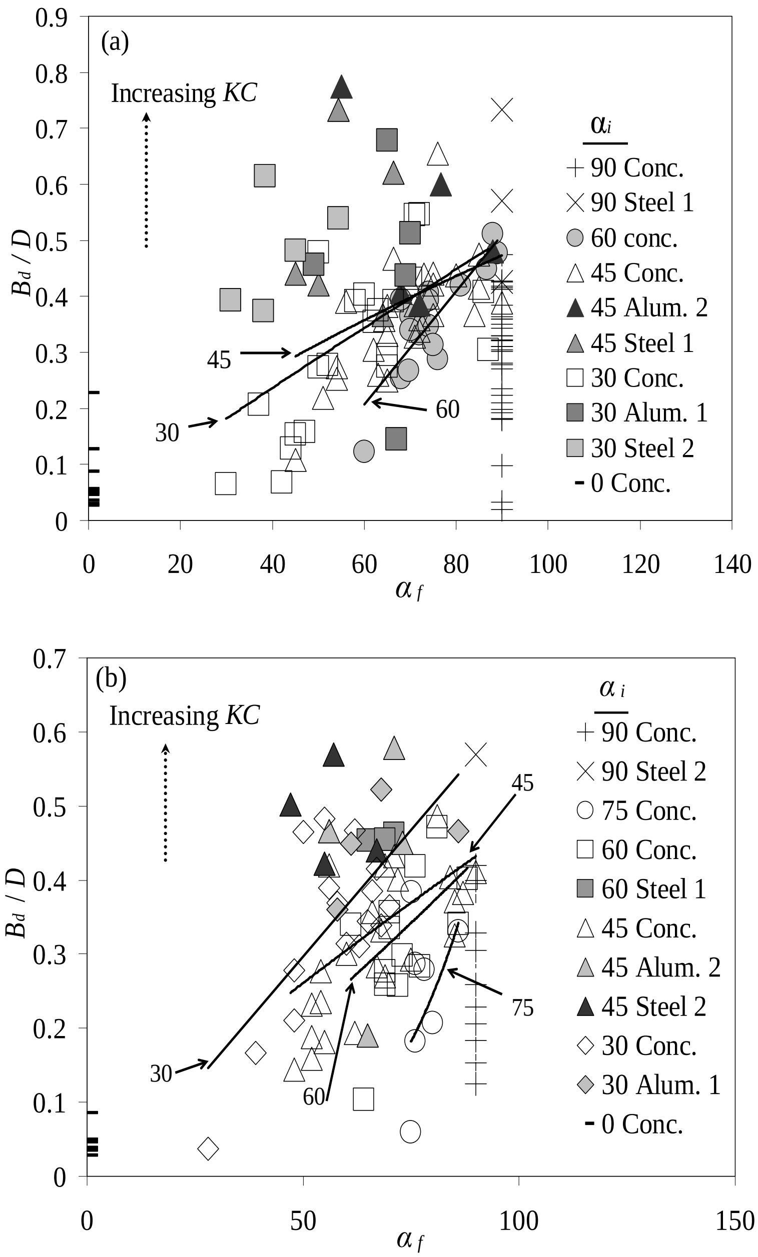


Fig. 6. Equilibrium dimensionless length of the scour hole as a function of KC. Comparison between predictive equation 2 and existing empirical formulae.



(a)

(b)

Fig. 7. Relative equilibrium burial depth as a function of the final and initial angles of attack. (a) for WA, (b) for CF.

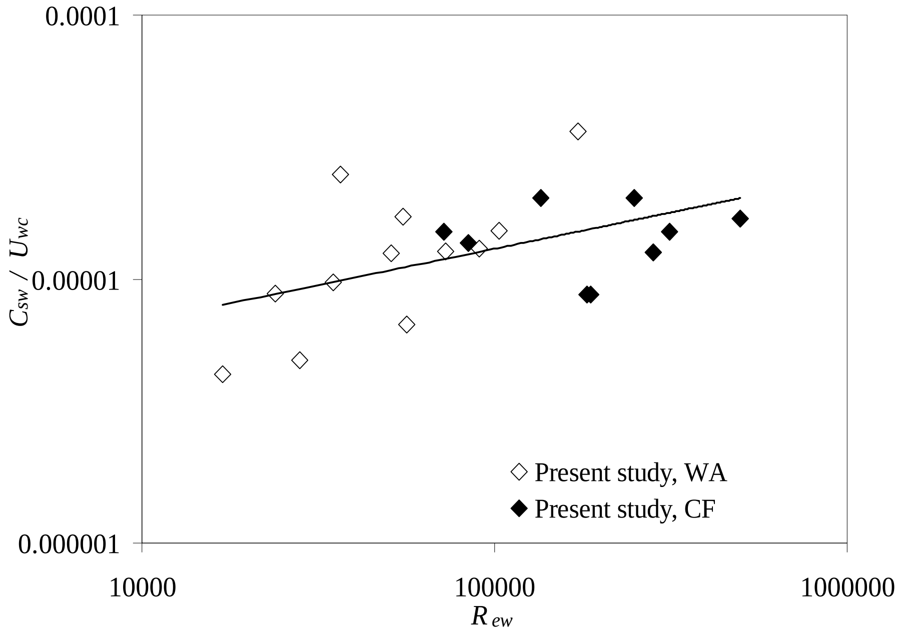


Fig. 8. Sand wave migration speed as a function of the Reynolds wave number, Rew = U a / ν, in which a is the particle orbital wave amplitude.

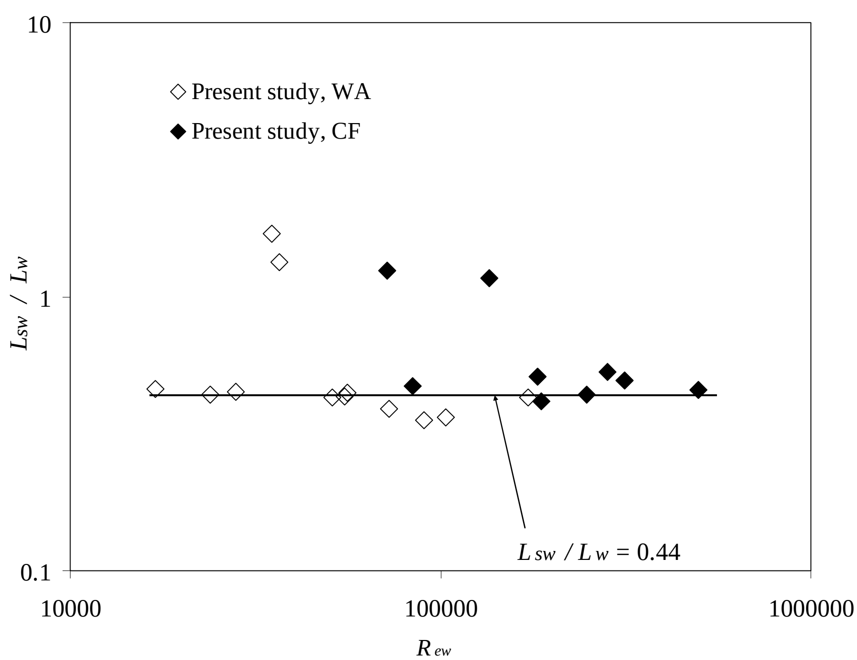


Fig. 9a. Dimensionless sandwave length as a function of the Reynolds wave number.

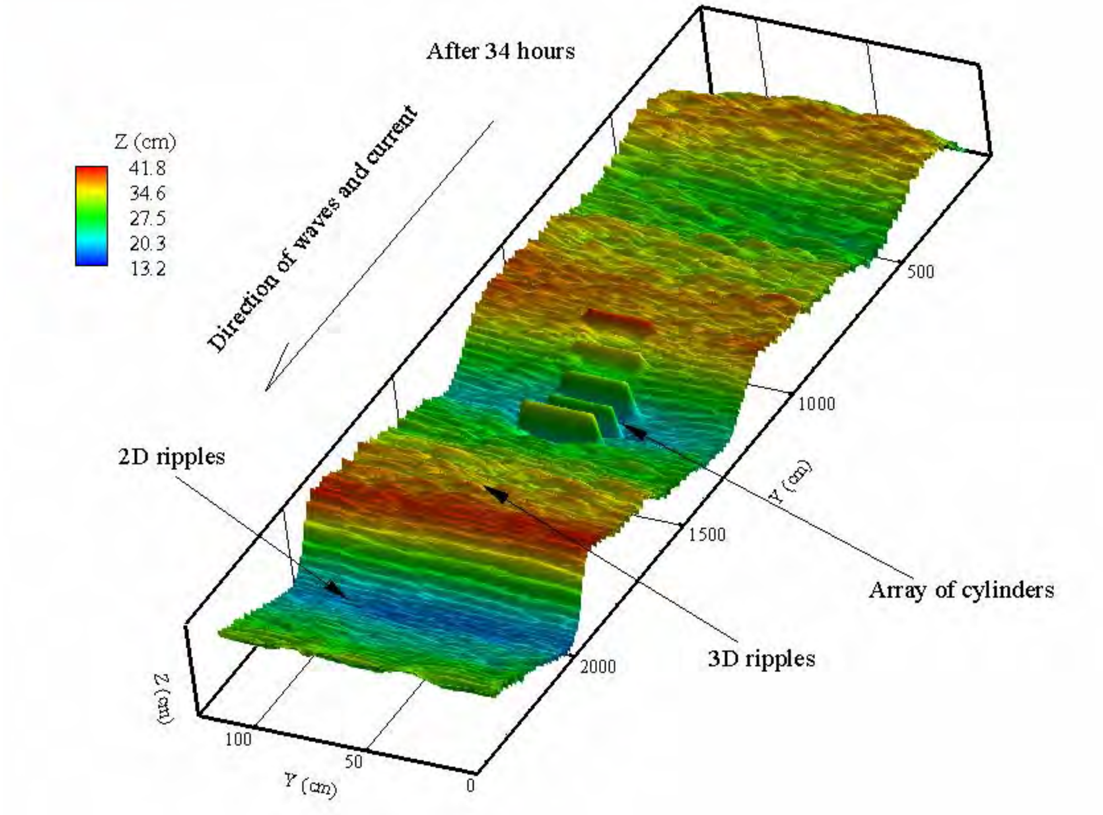


Fig 9b. Sandwaves and ripples pattern after 35 hours for combined flow. Hydraulic conditions: Uwc = 40.2 cm/s, Hw = 19.5 cm, Tw = 5.8 s, Lw = 17.2 m, h = 56 cm.

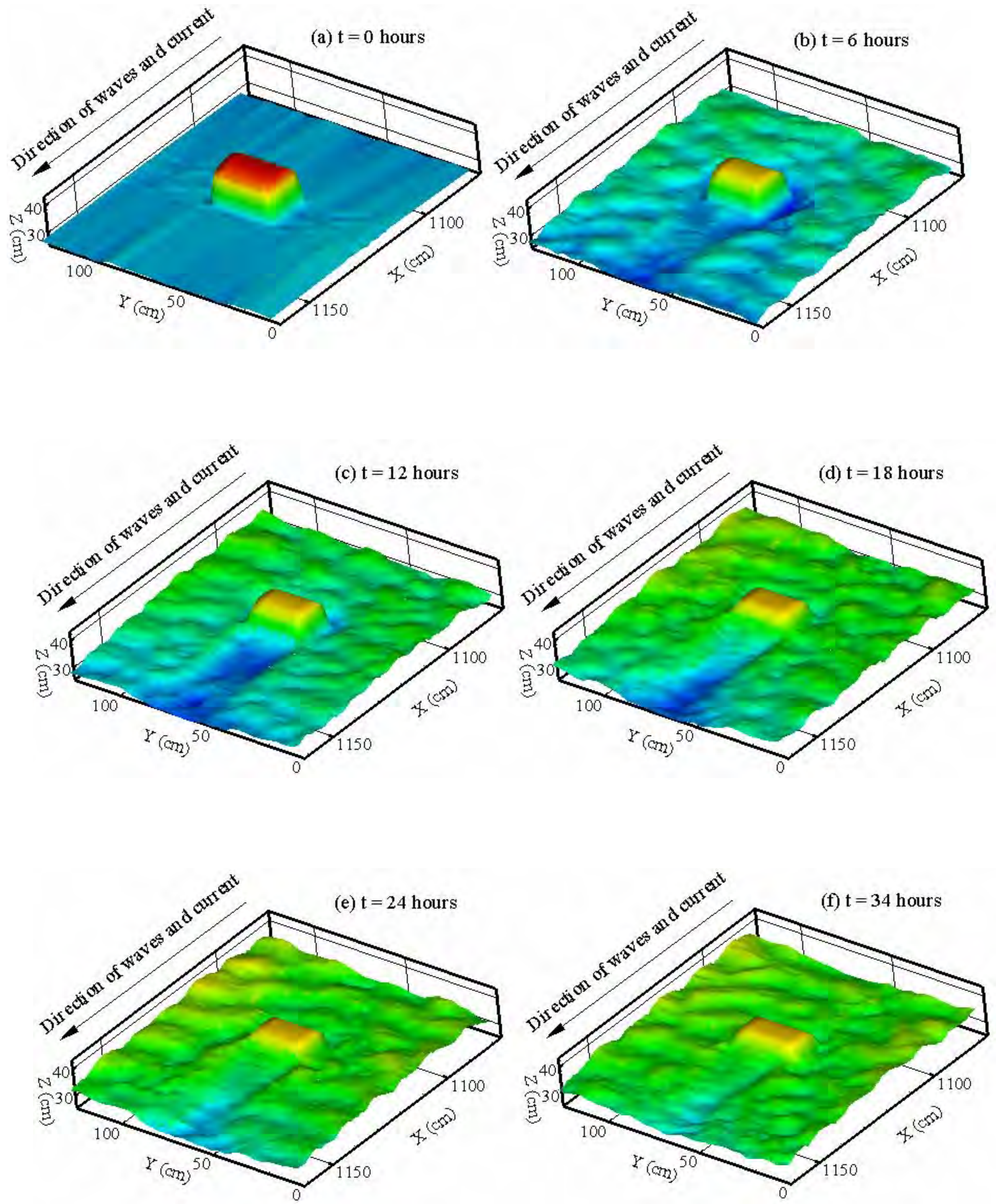
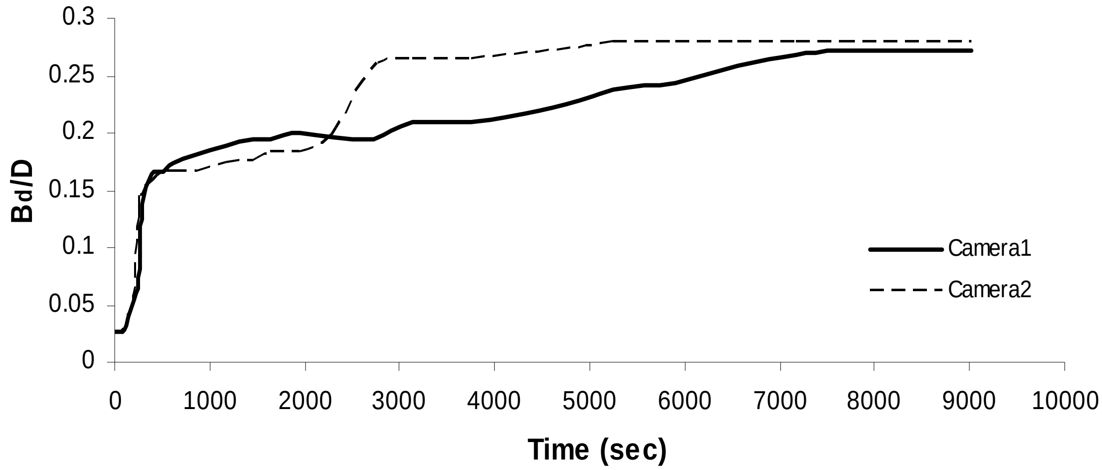
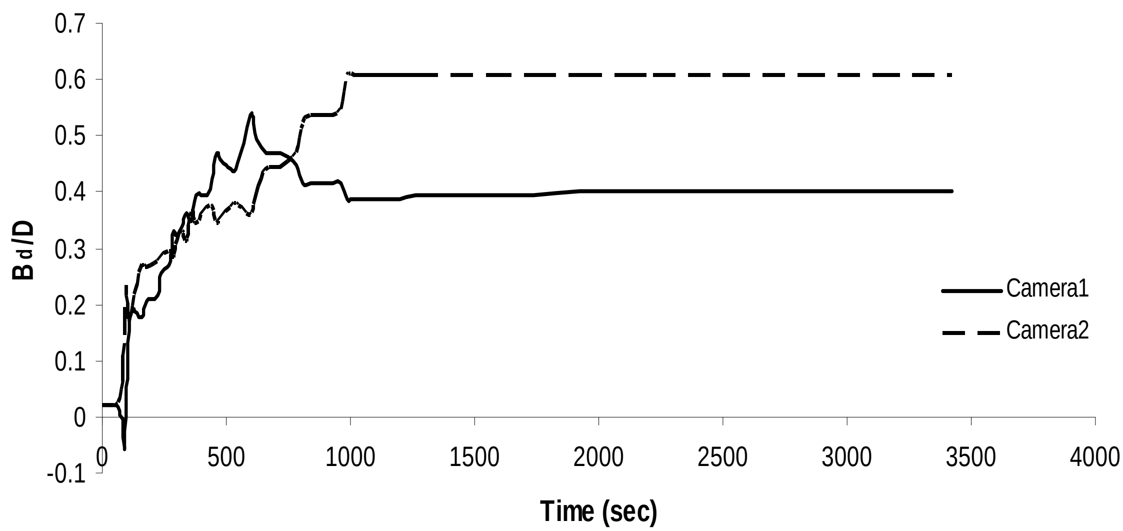


Fig. 10. Evolution over time of burial of cylinder due to local scour and burying due to passage of sandwave. Conditions: h = 56 cm, Hw = 19.3 cm, Tw = 5.8 s, Lw = 17.2 m and KC = 38. Cylinder 3 in Table 1. Case of combined flow, Uwc = 40.2 cm/s.



a) *Um* = 25cm/s, *Tw* = 4 s.



b) *Um* = 50 cm/s, *Tw* = 9 s.

Fig. 11. Evolution of cylinder burial over time. (Pure oscillatory flow).

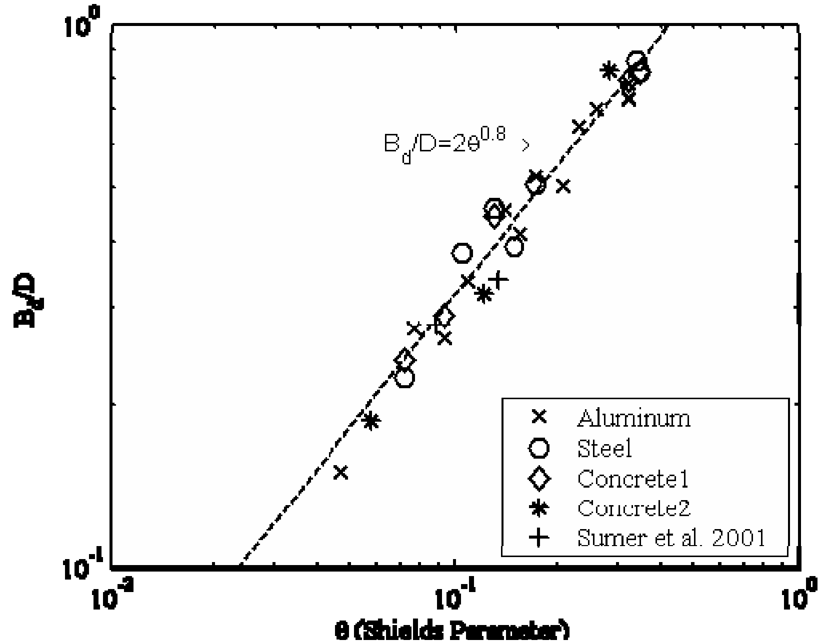


Fig. 12. Equilibrium relative burial depth (Bd / D) versus Shields parameter θ.

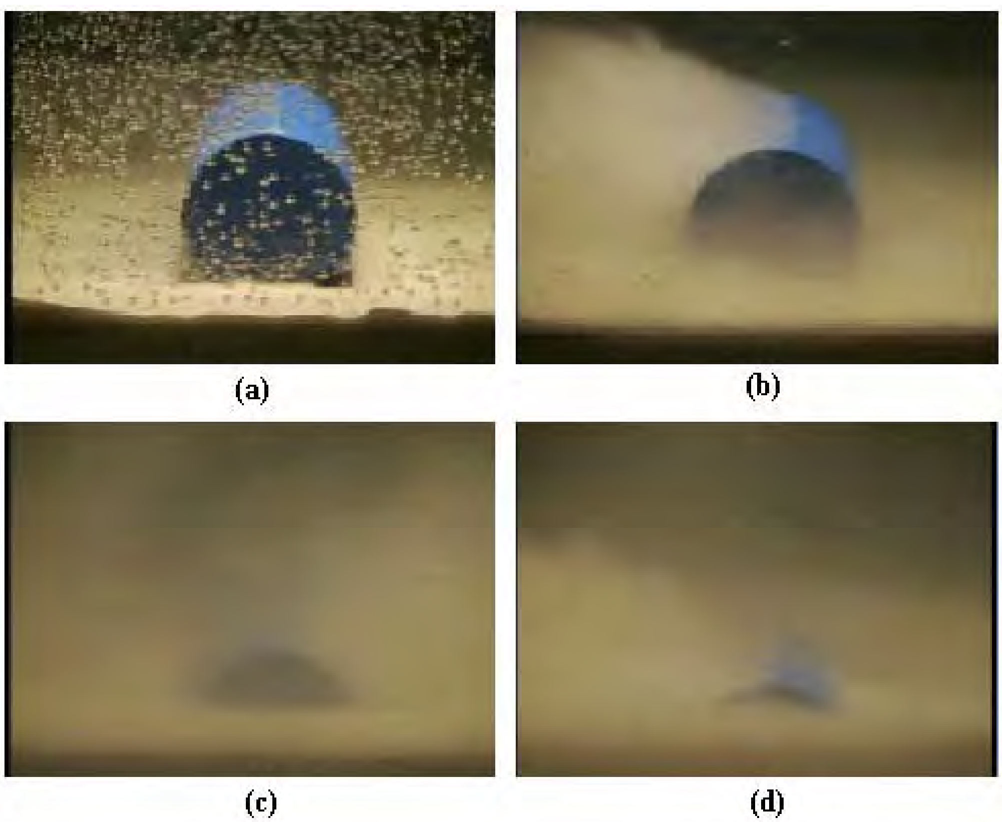


Fig. 13. Burial due to fluidization, Steel Cylinder, Um = 88 cm/s, Tw = 3.6 s. (a) t = 0 s, (b) t = 10 s, (c) t = 20 s, and (d) t = 35 s.